Tangible Globes for Data Visualisation in Augmented Reality

Kadek Ananta Satriadi
Monash University
Melbourne, Australia
University of South Australia
Adelaide, Australia

Jim Smiley
Monash University
Melbourne, Australia

Barrett Ens
Monash University
Melbourne, Australia

Maxime Cordeil
Monash University
Melbourne, Australia

Tobias Czauderna
Monash University
Melbourne, Australia

Benjamin Lee
Monash University
Melbourne, Australia

Ying Yang
Monash University
Melbourne, Australia

Tim Dwyer
Monash University
Melbourne, Australia

Bernhard Jenny
Monash University
Melbourne, Australia

Figure 1: We envision three general categories of how AR geospatial data visualisation can be supported by physical, tangible globes. The augmented globes category (left) puts information space on and around the tangible globe. The tangible globe input category (middle) utilises the spherical form-factor and tactility of the tangible globe to control virtual information space. The complex interplay category (right) combines the two, creating distributed information spaces. Note: virtual elements are illustrated in blue throughout the paper.

ABSTRACT

Head-mounted augmented reality (AR) displays allow for the seamless integration of virtual visualisation with contextual tangible references, such as physical (tangible) globes. We explore the design of immersive geospatial data visualisation with AR and tangible globes. We investigate the "tangible-virtual interplay" of tangible globes with virtual data visualisation, and propose a conceptual approach for designing immersive geospatial globes. We demonstrate a set of use cases, such as augmenting a tangible globe with virtual overlays, using a physical globe as a tangible input device for interacting with virtual globes and maps, and linking an augmented globe to an abstract data visualisation. We gathered qualitative feedback from experts about our use case visualisations, and compiled a summary of key takeaways as well as ideas for envisioned future improvements. The proposed design space, example visualisations and lessons learned aim to guide the design of tangible globes for data visualisation in AR.

CCS CONCEPTS

• **Human-centered computing → Visualization**.

KEYWORDS

immersive analytics, tangible user interface, augmented reality, geographic visualisation

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1 INTRODUCTION

Augmented reality (AR) has brought rich opportunities for novel interactive, engaging and embodied data visualisation. The ability to superimpose graphics onto physical objects allows for visualisation idioms that integrate virtual objects with contextual tangible references. This currently requires technical bespoke solutions, but integrating tangible props into data visualisation promises worthwhile design factors, including tactile feedback, contextual reference frames, and a novel experience. In this paper we explore the use of handheld globes for supporting geospatial data visualisation, motivated by the enduring popularity of physical globes and the opportunities presented by recent developments in AR, as discussed in Section 2.

Exploring AR visualisation with tangible globes is valuable for two reasons. First, data visualisations on virtual globes are compelling and have been used in many instances. These include data storytelling for news media [15, 23, 68, 81], AR demonstration [68], and professional data analytics tools [73]. However, such examples have been primarily used with conventional 2D displays; AR globes for data visualisation are very rare. Second, recent technology is sufficiently robust to combine AR with tangible objects, as demonstrated across a variety of interactive data applications in the recently flourishing field of immersive analytics [13, 70]. While spherical tangible user interfaces have recently been explored for use with immersive visualisation as reviewed in Section 3, the design space for visualising geospatial data with tangible globes and immersive AR has not been thoroughly investigated.

In this paper, we explore opportunities for combining the benefits of tangible globe interaction with the immersive visualisation capabilities of AR to create engaging 3D data visualisations. We draw inspiration from the array of recent examples of data visualisation on virtual globes to create a design space that describes the possibilities for "tangible-virtual interplay" between tangible globes and virtual data representations. We distil this space into three exemplary interaction categories defined by the relationship between control spaces provided by tangible input and the myriad of display space options allowed by immersive data visualisation.

Using prototype tangible globe devices, we further develop this conceptualised space by instantiating nine use cases. These demonstrate the breadth of engaging AR data visualisations with tangible globes. Together, our design space and prototype implementations address the research gaps on how to combine tangible globes and AR technology for data visualisation, by supporting the creation of tangible, interactive experiences with 3D data visualisations that enable data exploration and understanding in the context of physical and virtual globes. Qualitative feedback from experts provides initial reactions and suggestions for envisioned future improvements.

The contributions of this paper are as follows:

(1) A design space that encapsulates the dimensions for tangible globes and virtual data representations (Section 4).
(2) A conceptual approach for tangible–virtual interplay, which describes how information and control spaces are distributed and coordinated (Section 5).
(3) Example use cases, including technical implementation details, demonstrating the application of tangible–virtual interplay for creating useful and engaging data visualisations (Section 6).
(4) A list of lessons learned from a qualitative evaluation with data visualisation experts (Section 7), and ideas for envisioned future interactions based in part from participant feedback (Section 8.1).

The exploration presented in this paper aims to guide the design of immersive data visualisation supported by contextual tangible globes for various applications and possibly, spark deeper scientific discussions on this topic.

2 MOTIVATION

Tangible (or physical) globes have a long history as devices for displaying geographic information, with examples dating back to ancient Greece [97, 105]. Today, globes are a common fixture in offices, libraries and classrooms. Such tangible globes are popular, visually appealing and affordable models of Earth.

Modern display technologies allow for globes with digital spherical displays [3, 95, 106], some with a touch interface. These globes vary in size, ranging from small-handheld globes to building-sized globes, such as Eartha [24], which is claimed to be the largest rotating globe. While tangible globes with integrated electronic displays offer engaging interaction and endless possibilities for data overlay, their cost and complexity make them unlikely to ever become popular outside of museums or exhibition spaces. However, AR promises similar display and interaction capabilities without specialised hardware. While AR globes have been explored for education and training [54, 60, 72], and as commercial products [7, 74, 112], the current state-of-the-art head-mounted AR displays allow for more sophisticated user interaction and rendering of virtual objects that result in many engaging applications beyond education and training (see also Section 3).

Current AR head-mounted displays (HMDs) such as the Microsoft HoloLens 2 and Magic Leap have somewhat limited computing performance, image quality, and affordability, but they are nevertheless useful for exploring the potential of mixed-reality data visualisation since they provide a glimpse at the possibly not-so-far future of immersive visualisation. AR HMDs are mobile, may be used in different environments, and support hands-free operation. Furthermore, because AR HMDs move with the user, they enable data visualisation that is situated and egocentric [34]. The immersive three-dimensional display space for arranging charts, maps, and globes is virtually unlimited, which removes traditional restrictions on the number and size of such visualisations. Viewing three-dimensional visualisations with AR HMDs is also more natural than 2D screens thanks to stereoscopic rendering and head tracking.

For these reasons, we are interested in exploring the potential of AR for integrating geospatial data visualisation with tangible globes. While spherical tangible input can also be incorporated in virtual reality [30, 31], we seek to extend work in immersive data visualisation that integrates virtual objects with the physical environment [8, 9, 12, 49, 58, 84, 91].

3 RELATED WORK

3.1 Augmented Reality Data Visualisation

Augmented reality data visualisation and visual analytics have attracted considerable attention resulting in the recent *Immersive Analytics* [13, 70] research area. A number of dedicated tools and toolkits to create immersive data visualisations in AR have also emerged to accelerate the development of novel AR visual analytics systems [8, 18, 84, 90].

Research in immersive AR data visualisation has investigated the integration of immersive visualisations with traditional displays. Wang et al. [104] studied how an immersive AR HMD could be used as an extension to the 2D screen to analyse 3D visualisations of particle physics simulations. The results of their qualitative study showed that the AR HMD helped experts better understand complex physics phenomena. Langner et al. [58] proposed a framework for immersive visualisation with tablet devices and AR headsets. Their case studies demonstrated the value of extending limited physical screen displays and combining multiple devices for creating and controlling interactive 2D and 3D visualisations. Hubenschmid et al. [49] also combined AR with mobile devices. They explored various designs for overcoming the limitations of AR and 2D touch surface input.

The Microsoft HoloLens has also been explored to augment interactive visualisations on large collaborative displays. Reipschläger et al. [84] explored the use of the HoloLens for AR visualisation combined with a large wall-size display. Their visualisation extended the 2D display on the wall to 3D space for the exploration and analysis of multi-dimensional data. They use the third dimension to display additional data dimensions in space or display additional 2.5D visualisations. Similarly, Mahmood et al. [69] used AR on a large display to combine 2D and 3D spaces for the analysis of multivariate geospatial data.

Beyond extending 2D displays, some research has been done on projecting augmented visualisation onto physical objects, embedded in physical environments. Chen et al. [14] designed and implemented a workflow for augmenting static physical visualisations with virtual visualisations. The reported user study showed that the system was easy to use and achieved high user satisfaction. Kirshenbaum et al. [55] compared pseudo-3D terrain and physical 3D terrain visualisation for geovisualisation tasks and found that the 3D visualisation better supported the tasks by providing physical shapes for the data.

Overall, previous work shows that AR data visualisation allows visual analytics to go beyond traditional 2D screens, demonstrating the flexibility and versatility of immersive analytics for data exploration. It also appears that the combination of immersive embodied visualisations and 3D conventional physical environments enhances user perception and comprehension of data.

3.2 Tangible Interaction for Augmented Reality Visualisation

Tangible objects have been previously explored as novel means to support interaction and computing with systems beyond traditional 2D desktop interfaces [48, 51, 56, 100]. The concept of *embodied interaction* [21] emerged in the early 2000s and described how manipulating tangible artefacts (especially in social contexts) opens up new perspectives in human-computer interaction to perform interactive tasks.

Embodied tangible interaction with augmented reality content was defined as a mapping between virtual and physical objects [5]. Tangible AR has been shown to facilitate user interaction with a virtual object via physical object manipulation [4, 22, 44, 59]. Some early visualisation systems that use tangible object interaction with projected augmented reality have been explored. For example, Ullmer et al. [101] designed a tangible *embodied queries* visualisation interface in which the user can bind physical controls such as sliders and knobs to data to perform data queries and filtering operations.

With the emergence of modern, affordable AR and VR headsets, researchers have explored tangible interaction and dedicated input devices for augmented reality data visualisation in the field of Immersive Analytics. Cordeil et al. [17] proposed a design space of tangible input for AR visualisation and demonstrated exemplar devices that combine a tracked touch cube to control a 3D scatterplot. This work was later extended by Smiley et al. [91], who proposed composable controllers with actuated sliders for creating multi-dimensional visualisations in VR and AR. Bach et al. [1] studied how tangible AR visualisations affect user performance for 3D visualisation tasks and found that participants performed better when coupling AR visualisation with the Microsoft HoloLens and tangible input. Cordeil et al. [16] refined the design of the 3D-axes device and demonstrated how the tangible device improved the user's accuracy on data visualisation selection tasks in AR.

For geographic data, seminal papers such as those by Looser et al. and Hedley et al. demonstrated how tangible interfaces can be used to explore virtual globe visualisations [64, 65] or 3D maps [45]. Tangible AR visualisations of geographic data have also been demonstrated in combination with tabletop displays. Ssin et al. [96] combined a tangible interface with tabletop and AR displays for space-time cube visualisations and found that their system improved user's reading accuracy for correlation estimation tasks. Theriot et al. [99] demonstrated a system that combines 3D printed terrain and tangible controllers placed on a tabletop-projected AR. Satriadi et al. [89] evaluated quantitative data visualisation on virtual globes and envisioned immersive visualisation where virtual bars are arranged around a tangible globe. We build upon this work with a deeper exploration of the design space.

3.3 Spherical Tangible Devices

The use of tangible, physical globes has been explored in HCI for educational purposes. Yamashita et al. [108] combine a tangible globe and a tangible avatar to control the day-night cycle of a 3D virtual environment on the desktop screen. A more recent study extended their system with a more advanced tangible avatar whose gaze directions can be controlled with embodied actions [57]. Other researchers demonstrated benefits for educational tools by combining AR globe with mobile device [71] and using small physical planets that students can arrange on a table [75].

The use of spherical tangible displays has been explored for user interaction input and display output. Spherical displays include projected displays and electronic pixel-based displays. Early work demonstrated geospatial network visualisation on a projected spherical display [111]. More recent work in projected spherical displays is capable of correcting the distorted image to create an illusion of 3D objects inside the sphere [10, 40, 67]. The hand-held perspective-corrected spherical display was even found to be accurate for 3D object manipulation tasks [66]. The exploration of electronic spherical display includes its challenges and opportunities for visualisation [103, 106] and user interaction techniques [3, 94]. Another interesting early work is Cybersphere [39], an immersive display which encloses the user in a room that is akin to a "hamster ball".

We are interested in utilising space around the tangible globe and around the user. Hence, we focus on existing work that used head-mounted AR and VR displays. Work by Englmeier et al. [26] is strongly related to this. They used a transparent sphere as an input controller for various applications, including virtual spherical displays [25, 29], tangible spherical controllers [25, 27], and, to some extent, data visualisations [25, 31]. In a position paper, Englmeier et al. [25] proposed opportunities of using spherical tangible input devices in which they show a 3D bar visualisation on a virtual globe. Their follow-up research investigated small and medium spherical input to enhance perception of spherical data visualisation in VR by the example of a simple globe, a network, and a 360° video [31]. Despite these previous works, the design of data visualisation with tangible globes in augmented reality that go beyond placing virtual objects on the globe has not been thoroughly explored. Our work intends to fill this gap by proposing a design space, describing tangible-virtual interplay scenarios, and implementing use case visualisations.

4 DESIGN SPACE

The combination of tangible globes and virtual data visualisations opens up numerous design possibilities. Based on our review of prior work involving tangible objects and globe-based data visualisations, we introduce a design space for describing the interplay between tangible globes and virtual data visualisation. This section identifies the dimensions of both components. The following section defines three main categories of interplay between them.

4.1 Tangible Globes

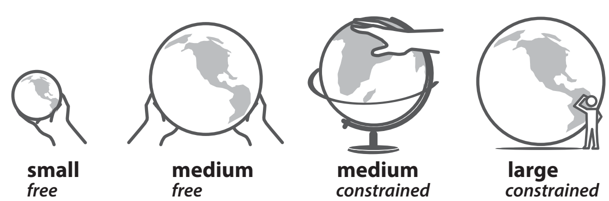

Figure 2: Tangible globes at *small, medium* and *large* sizes. Position and orientation are *free* or *constrained.*

For tangible globes we identified three design dimensions: *size*, *constraints of position and orientation*, and *interaction modes*. The size dimension has an effect on the two other dimensions. For example, interaction modes are different for small and large globes.

Size. Physical globes exist in a variety of sizes (Figure 2); a common diameter is around 25 cm [41]. Globes at this size are easy to acquire and are commonly used for educational purposes, while large globes are expensive and mainly found in museums or other public venues [24, 47]. A *small* tangible globe can be held with a single hand, freeing the other hand, for example, to point or perform other gestures. A *medium*-sized tangible globe is too large to be grabbed with a single hand and needs two hands to be comfortably held. A *large* globe cannot conveniently be held with two hands, and can be human-sized or even larger.

Constraints of position and orientation. The degrees of freedom for position and orientation include the three axes of *rotation* (*yaw*, *roll*, *pitch*), and the three *translation* directions (x, y, z). Considering that the average human hand grasp is 7 cm wide [38], hand-held small globes are *free* of position and orientation constraints altogether [29, 31]. Medium-sized tangible globes are commonly mounted on a base, resulting in *constrained* orientation around one or two axes of rotation. A single gimbal arm for yaw-only rotation around the polar axis is by far the most common form (Figure 2). Very large globes are typically fully *constrained*, as they are too large or too heavy for tangible interaction.

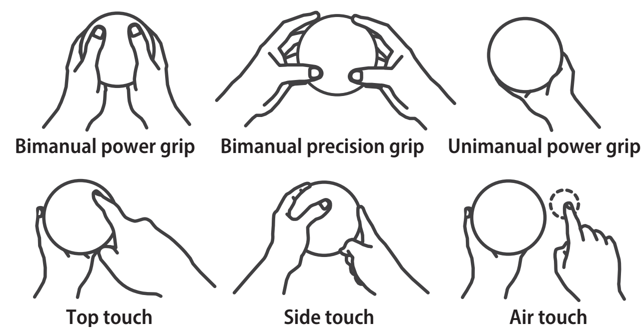

Figure 3: Touch interaction modes for a small globe: power grip vs. precision grip, bimanual vs. unimanual, surface touch vs. air touch.

Interaction Modes. Tangible AR is often multimodal [113]. In addition to *translation* and *rotation* manipulations, tangible globe interaction can include hand gestures such as *touch*, *swiping*, *shaking*, and *air touch* (pointing and swiping on the virtual surface) for natural and intuitive manipulation [113]. While sensors embedded in AR headsets can add non-tangible input modes, such as *gaze*, *natural language*, or *proxemics* [52], we focus here on interaction modes that are specific to tangible spheres.

The affordance of touch interactions varies with the size of the globe. For hand-held small and medium-sized globes, it is useful to distinguish between power grip and precision grip postures [77]. With a power grip, the palm touches the globe, resulting in strong grip, whereas with a precision grip, only fingers touch the globe, allowing for precise control (Figure 3). Object grabbing can be unimanual (one-handed) or bimanual (two-handed). The unimanual power grip can be performed on the bottom, side, or the top of a tangible globe. With bimanual interaction, the user can perform touch actions on a specific region of a tangible globe, or with AR, in the empty space around the globe (air touch).

4.2 Virtual Data Visualisation

We identified five design dimensions for virtual data visualisation for globes: *visualisation idiom*, *reference frame*, *orientation*, *multiplicity* and *size*.

Idiom. A visualisation idiom is a distinctive visual representation of a data set [76]. Traditional physical globes can show a variety of cartographic idioms, such as choropleth or geographic flow visualisations. AR can augment tangible globes with a variety of additional two-dimensional and three-dimensional visualisation idioms, for example, *3D bar chart* or *scatterplot*. For instance, a visualisation proposed by Englmeier [25] uses three-dimensional bars perpendicularly on the surface of a tangible globe to show quantitative values at specific locations.

Reference Frame. The spatial reference frame denotes where a virtual data visualisation is anchored [33, 37]. We borrow terminology from the "continuum of display spaces" by Zhu and Grossman [114], who combined head-mounted AR with a smartphone to place information on the phone, around the phone, and in the spatial environment. We adapt and extend this continuum to tangible globes. Our adaptation places visual data representations *above* the tangible globe, *around* the tangible globe, *side-by-side* to the tangible globe, *overlays* visualisations on the tangible globe, and positions visualisations at fixed positions in the *environment*.

Orientation. Virtual visualisations can be oriented in different ways relative to the tangible globe. They can be attached to the globe surface, in which case their orientation is *coupled* to the globe's orientation, they can always show the same face to the camera and create a *billboard* orientation, they can allow for *free* orientation, or their orientation and position can be *fixed*.

Multiplicity. One benefit of using virtual objects is that we can create multiple copies and arrange them in the abundant space around the user. The number of virtual objects can increase with the complexity of the visualisation. While a univariate geographic dataset may require a *single* visualisation, a multivariate or temporal dataset can be visualised with *multiple* virtual globes.

Size. In AR, the size of the virtual visualisation is limited only by the surrounding available space, but the position of the virtual visualisation and the size of the tangible globe should be taken into account. For instance, with a small tangible globe, it makes sense to display a visualisation on a large virtual globe fixed in the external physical space rather than placing a visualisation on the limited surface of the small globe.

5 TANGIBLE-VIRTUAL INTERPLAY

The combined design dimensions of tangible globes and virtual data visualisations provide a large design space to explore. Because most innovations of our use cases are in virtual data visualisation, our use cases make little variations of the three tangible globe design dimensions (i.e., globe size, constraints of position and orientation, and interaction modes). Figure 4 therefore focuses on the virtual data visualisation design dimensions.

Figure 4 outlines the virtual data visualisation dimensions applied by our use cases (top) and those applied by a set of related papers (bottom). Although there is a significant body of work on spherical displays [3, 36, 61, 62, 103] and perspective-corrected spherical displays [10, 40, 66, 67], we excluded these papers from our comparison. Here we focus on spherical input devices combined with head-mounted displays for VR and AR, because this allows for more flexible placement of virtual visualisations.

To further conceptualise our exploration, we distil the design space into three distinctive categories: *augmented globes*, *tangible globe input*, and *complex interplay*. This grouping is primarily based on how information and control spaces are distributed and coordinated. The information space contains the visual representation of the data. It is where the user mainly focuses their attention. The control space enables the user to manipulate the information space, for instance, to manipulate the visualisation views [11].

Each category represents a range of interaction possibilities, which we show with multiple example use cases. Each use case is accompanied by an interactive demonstration we implemented using the tangible globe prototype and a Microsoft HoloLens 2 head-mounted AR display. Before describing the prototypes in more detail, we first give an overview of each category and related example use cases.

5.1 Augmented Globes

In the augmented globes category, *the tangible globe serves as the main information space, which is augmented by virtual objects* (Figure 1, left). Regardless of the *size* and *constraints on position and orientation* of the tangible globe, the virtual data visualisations are positioned *above* the globe, in the space immediately *around* it, *side-by-side* to the globe, or *overlaying* the globe (Figure 5).

The first use case **(A1)**[1] places virtual visual marks above the surface of the tangible globe to create a geographic idiom (Figure 5, top-left).

The second use case **(A2)** creates a composite visualisation by placing a virtual visualisation in the space around the tangible globe (Figure 5, top-right). A composite visualisation is defined as a composition of multiple visual structures that share a common view [53]. In this use case, the view is an integration of a physical view (tangible globe) and a virtual view. The tangible globe could show simple political borders, a thematic map [103], or it could be a data physicalisation [20].

Another use case **(A3)** is motivated by the fact that only half of a globe is visible at any time. With an AR display, we can show the hidden hemisphere of the tangible globe using a virtual replica in a side-by-side configuration (Figure 5, bottom-left).

The last use case **(A4)** places a virtual visualisation overlaying the entire surface of the tangible globe (Figure 5, bottom-right). This has been demonstrated in previous work [30, 31] and is useful for a wide range of applications, including stylising the appearance of a globe or visualising planetary surfaces.

[1]Use cases for **A**ugmented globes are indicated with **A**, those for **T**angible globe input with **T**, and **C**omplex interplay use cases are indicated with **C**.

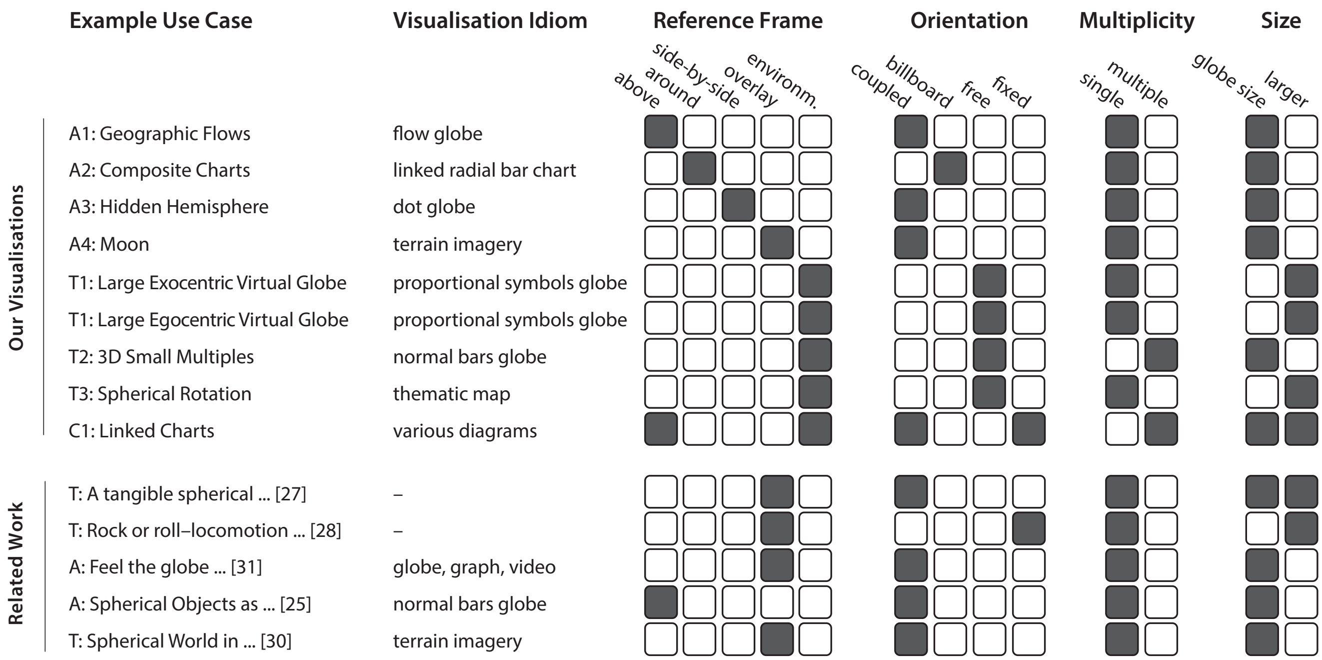

Figure 4: Design space: virtual data visualisation as applied by examples that we present as well as existing examples from related work. The label for each item in the leftmost column indicates the category of interplay (A: augmented globes, T: tangible globe input, C: complex interplay). A filled cell indicates the design dimension option used. Most included existing works use a transparent spherical tangible user interface.

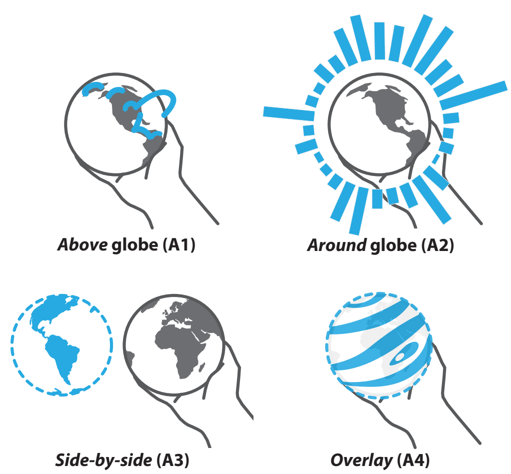

Figure 5: Geographic marks *above* the surface of a tangible globe (A1), a diagram *around* a tangible globe (A2), a virtual thematic globe placed *side-by-side* with a thematic tangible globe (A3), and a virtual texture *overlaying* the surface of a tangible globe (A4).

5.2 Tangible Globe Input

In the tangible globe input category, *the tangible globe serves solely as a tangible input controller while the virtual data visualisations are located in a separate information space* (Figure 1, middle). This type of interaction takes advantages of the globe's tangibility and allows for a broad variety of virtual data representations of varying geometry, size, or multiplicity, without being limited by the specific form of the tangible globe. Users can perform eyes-free manipulations using the virtual sphere, while focusing their attention on the virtual data representation. The work by Englmeier et al. also uses a spherical tangible user interface for virtual object manipulation [27] and locomotion in virtual environments [28]. We extend the work by proposing several new use case scenarios for tangible globe input techniques.

The first use case **(T1)** manipulates a large virtual thematic globe with a tangible globe (Figure 6, left). Previous work in data visualisation [46, 89] suggests that larger visualisations improve users' reading accuracy. Bringing virtual globes into AR allows for large, immersive visualisations. In this use case, the grip affordances of a small tangible globe provide an alternative to in-air pinch and drag gestures for controlling a large virtual globe visualisation. The free 6 DoF manipulation of the tangible globe can be mapped to a virtual globe with fewer degrees of freedom, including any desired translation or rotation constraints.

The second use case **(T2)** involves the control of 3D small multiples visualisations (Figure 6, middle). Small multiples is a visualisation technique that facets the views based on the values of a categorical or ordinal attribute. In virtual reality or augmented reality, the small multiple technique can be used for 3D visualisations, for instance, 3D bar charts [63]. Rotation is an intrinsic requirement for 3D visualisations. In the case of small multiple, it is reasonable to synchronise the rotation of all views.

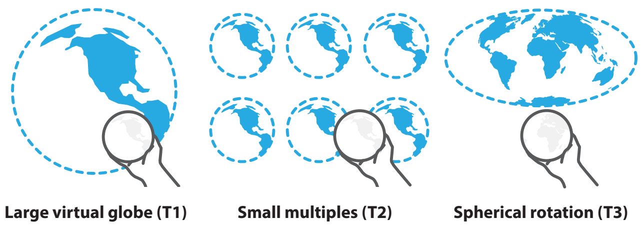

Figure 6: Tangible globe as a means to control a large virtual thematic globe (T1), small multiple 3D visualisations (T2), and the spherical rotation of a map projection (T3).

The third use case **(T3)** uses the tangible globe to control the centre and orientation of a map projection. A map is the result of a projection transforming a 3D globe to a 2D plane. The rotation of the sphere determines the orientation of the globe prior to the projection, resulting in varying the central latitude and longitude of the projected map. Despite the inherent mapping to a 2D plane, this rotation is a 3D interaction. In this use case, we can directly use the rotation angles of the tangible globe as the input parameters of the spherical rotation to provide intuitive control of the map centre.

5.3 Complex Interplay

In the complex interplay category, *information visualisation is shared between a tangible globe and virtual data visualisations.* Complex arrangements of multiple coordinated views [19] can be created by combining data visualisation placed on the surface of a tangible globe with data visualisations placed in the surrounding space. The tangible globe can play multiple roles for input control, such as proxemic interaction with nearby data representations [43], or indirect manipulation of virtual maps or globes.

Our use case **(C1)** is the exploration of multivariate data using linked charts (Figure 1, right). In this use case, we imagine an augmented globe held by the user which is linked with virtual abstract charts anchored in the physical environment such as on a wall or on a 2D screen. The augmented globe provides a geospatial context of the data while virtual charts such as scatterplots or bar charts encode complementary abstract data.

6 INTERACTIVE DATA VISUALISATIONS

To exemplify the use cases defined above, we created an interactive data visualisation for each use case. Each example uses an existing data set to demonstrate how tangible-virtual interplay can be used to support data exploration. These examples incorporate an interactive tangible globe prototype we built to support our demonstration.

6.1 Tangible Globe Prototype

To enable our exploration of tangible-virtual interplay, we designed and implemented a platform for augmenting tangible globes with AR data visualisations. The architecture of the platform (Figure 7) consists of a tangible globe tracking system (Vicon tracking system, QR marker, custom tangible globes), HoloLens 2, and an application component (Unity).

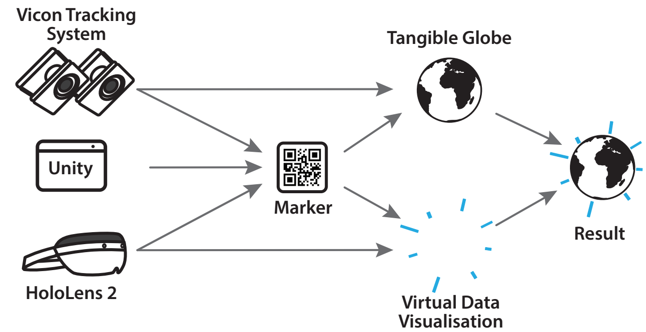

Figure 7: General system architecture. The QR code marks the shared known location between the Vicon tracking system and Microsoft HoloLens 2, allowing tangible globe and virtual data visualisation to be properly aligned.

Custom Tangible Globes. Existing works [25, 27–29, 31, 32] use an HTC Vive tracker placed inside a transparent ball. We aim to create a user experience with textured tangible globe and placing the Vive tracker inside the sphere would require a globe texture that is penetrable by IR light. Initially, we procured tangible globes from online stores and attached flat optical tracking markers to the surface. However, these trials showed the required size and number of reflective markers were too conspicuous, and more generally, reflections from the glossy surface of the globes interfered with the Vicon cameras, resulting in unstable tracking.

We therefore decided to assemble custom 3D printed tangible globes with hidden active tracking markers. Figure 8 shows the components. We embedded the globe with infrared LEDs (Figure 8, A). To power the LEDs, we used a 1200 mAh rechargeable battery and added a simple system using an ESP32 microcontroller board with inbuilt battery charging circuit, an accelerometer that monitors for initial movement and triggers a relay board (Figure 8, B) that turns the globe on and off for preserving battery power. Illuminated pushbuttons are hidden beneath the poles for future interaction possibilities (Figure 8, C). A changed state is streamed by the ESP32 as a UDP broadcast using the Open Sound Control protocol. For a seamless user experience, we installed a wireless charging receiver (Figure 8, E) in the tangible globe and built a wireless charging stand.

We designed stylised maps of populated places using Natural Earth data [79] and QGIS[2]. Then we printed gores [98] using the sinusoidal projection with 15° spacing with NASA's G.Projector software [78], and glued the gores onto the 3D printed sphere to create a custom globe. Our tangible globes weigh 250 grams each. We provide technical details and assembly instructions of the tangible globe in Supplementary Material 1.

AR Tracking and Alignment with the Globe. It is vital that the AR content is spatially aligned with the tangible globe as accurately as possible. We used a Microsoft HoloLens 2 AR headset for our virtual

[2]https://qgis.org/

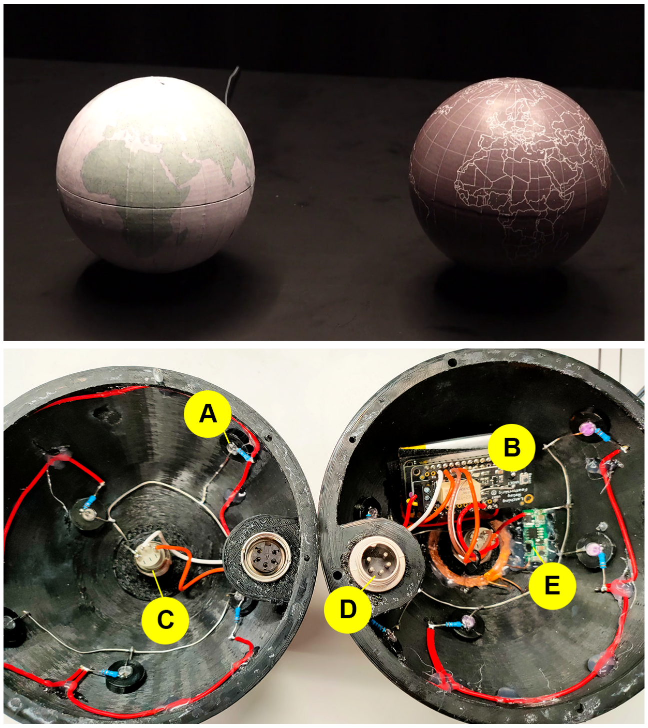

Figure 8: Our light and dark tangible globes placed on wireless chargers (top). The interior of the tangible globe consists of off-the-shelf components (bottom). A: infrared LEDs and resistors in parallel; B: ESP32 board, latching relay board, accelerometer, and 1200mAh battery; C: illuminated push-buttons; D: panel mount connectors; E: wireless charging receiver.

visualisations, in conjunction with a state-of-the-art Vicon tracking system to determine the position and rotation of the tangible globe in the 3D space. These values are wirelessly sent to the HoloLens in real-time, using UDP[3] for minimal latency. To align the two coordinate systems, we used a printed QR code overlaid with optical tracking markers, which were used to set the origin and orientation reference of the Vicon, and the inbuilt QR code tracking of the HoloLens 2 to achieve the shared reference.

Applications. Our AR prototype was developed using the Unity3D game engine. We used the Mixed Reality Toolkit[4] to facilitate basic AR functions, extOSC[5] for wireless communication, and wrote custom scripts for the data visualisations. We make all necessary applications to replicate the use cases publicly available[6].

6.2 Use Cases

We implemented data visualisation use cases discussed in Section 5. These visualisations allowed us to obtain first-hand experience of our vision as well as to showcase it to a broader audience. We present four visualisations (A1, A2, A3, A4) for the augmented globes category, three visualisations (T1, T2, T3) for the tangible globe input category, and one visualisation (C1) for the complex interplay category. Footage of all use cases captured from the Microsoft HoloLens 2 are provided in Supplementary Material 2.

A1: Geographic Flows. This prototype demonstrates the augmented globes use category where a geographic visualisation idiom, in this case lines representing flows, is positioned above the surface of the tangible globe (Figure 9). We use a global bilateral migration dataset [107] and only show flows with a minimum of 4,000 migrants in the year 2000 to reduce visual clutter. The design of the flow idiom follows recommendations from a recent study where the height of flow lines was mapped to the distance between the target and destination [109]. To indicate direction, we use colour and animated line segments.

Figure 9: Virtual flows aligned above the surface of the tangible globe (A1). Data: global bilateral migration [107][7].

A2: Composite Charts. This use case demonstrates a scenario where an abstract chart idiom is placed around the tangible globe (see Figure 10). This example is inspired by Geoburst, a globe visualisation originally designed for conventional 2D displays. It arranges a radial bar chart around a globe for visualising quantitative values [89]. For geographical context, lines link bars in the diagram with the corresponding locations on the globe. We use a tangible globe showing Natural Earth's populated places [79]. The arrangement of the bars is optimised every time the globe is rotated beyond a specific threshold angle, and bars for locations that are not currently visible on the globe are shown with reduced colour saturation.

A3: Hidden Hemisphere. This prototype demonstrates an augmented globe scenario where a virtual thematic globe is positioned side-by-side with the tangible globe. In our implementation, the virtual globe shows the hidden hemisphere of the tangible globe, allowing for switching the attention between hemispheres more easily than would be possible by rotating the globe (Figure 11). While we only show simple geographic boundaries and cities for both the tangible and the virtual globes, this use case is also promising for augmenting tangible globes that show more complex information.

[3]https://datatracker.ietf.org/doc/html/rfc768
[4]https://github.com/microsoft/MixedRealityToolkit-Unity
[5]https://github.com/Iam1337/extOSC
[6]https://kadeksatriadi.com/tangible-globe-ar
[7]Figures 9 to 16 were created by combining images from a tracked camera and Unity.

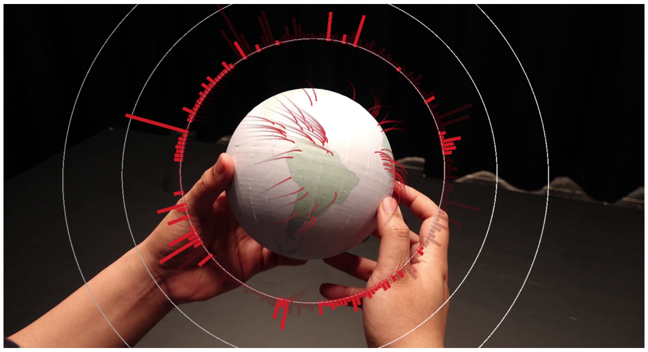

Figure 10: Composite visualisation using a tangible globe surrounded by a linked virtual radial bar chart (A2). Data: global city population [42].

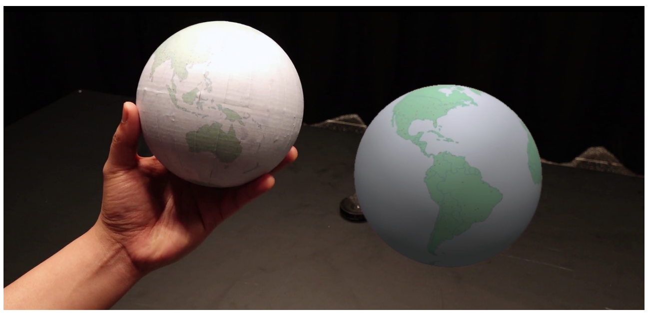

Figure 11: Tangible globe side-by-side with a virtual globe which shows the hidden hemisphere of the tangible globe (A3).

A4: Moon. Having the earth-map printed permanently on the surface of the globe gives a persistent reference object for many applications of augmented overlays, however, the permanent map may also be perceived as a limitation. To demonstrate the flexibility of virtual data representations, we demonstrate a different texture-map overlaid on the globe. In this use case, we overlaid the entire surface of the tangible globe with a texture of the surface of Moon in augmented reality (Figure 12). We found the bright (light grey) moon map completely obscured the earth map, meaning it can usefully be reused for other planets or non-earth data.

T1: Large Virtual Globe. This globe visualisation is inspired by an existing earthquake data [102] visualisation by Nicola [82]. Each earthquake centre is represented as a circle and its depth is exaggerated as well as colour-coded. The area of the circles is proportional to the magnitude of the earthquake.

We created two types of virtual globes: *exocentric* and *egocentric* (see Figure 13). The exocentric globe is what is commonly referred to as a virtual globe while the egocentric globe is a large globe enclosing the user [110]. For both types of globes the landmass is shown and the body of water is made transparent, allowing the user to see the points on the exocentric globe and minimising motion sickness for the egocentric globe as reported for such globe visualisations [110].

Figure 12: Tangible globe's texture is replaced with virtual information placed as an overlay on its surface (A4).

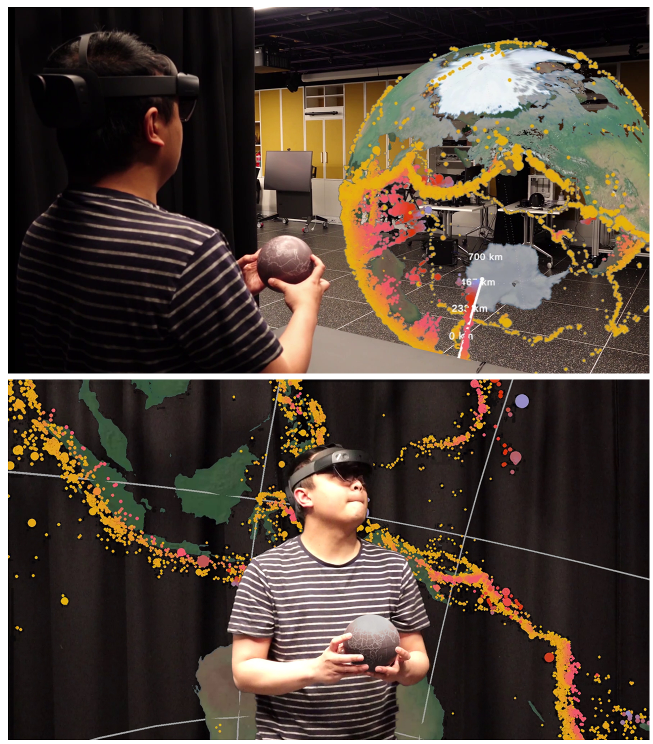

Figure 13: Exocentric (top) and egocentric (bottom) virtual thematic globe (T1). Data: global earthquakes [102].

T2: 3D Small Multiples. In this use case, we use a tangible globe for controlling the rotation of small multiple globe visualisations. We visualise a Global Health System dataset [35] using 11 virtual globes with normal bars [89] representing various attributes (see Figure 14). The rotation of all virtual globes is synchronised with the rotation of the tangible globe. The type of visualisation is not limited to virtual globes (e.g. 3D bar charts, 3D fields, space-time cubes) but the virtual globe is a good example due to its nature of three degrees of freedom for rotation.

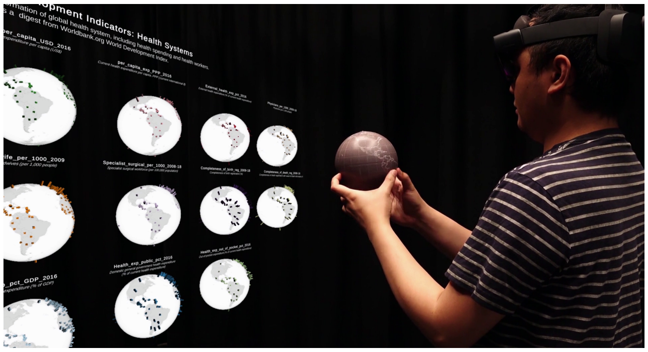

Figure 14: Tangible globe as an input device for small multiple visualisation (T2). Data: Global Health Systems [35].

T3: Spherical Rotation. In cartography, a spherical rotation can be applied to the sphere before it is projected to a flat map [92]. The result of this spherical rotation differs from conventional two-dimensional panning, where the entire map is translated. With a spherical rotation, the points on the projected map are translated in different directions. The spherical rotation is perceived as a transformation of a 2D map, while in reality, it is the result of rotating the globe. In this use case, we demonstrate how spherical rotation can be used with a tangible globe to adjust the centre and orientation of a flat virtual map.

We use a tangible globe with a texture and create a virtual map with a Hammer [93] projection. To create an engaging example, we use a flow map (Figure 15) and align the texture on the tangible globe with the centre of the map. The orientation angles of the tangible globe are mapped to the lambda, phi, and gamma parameters [6] of the spherical rotation applied to an invisible virtual sphere before the Hammer projection transforms the invisible sphere to a visual flat virtual map. The centre of the tangible globe as seen by the user is also the centre of the flat map.

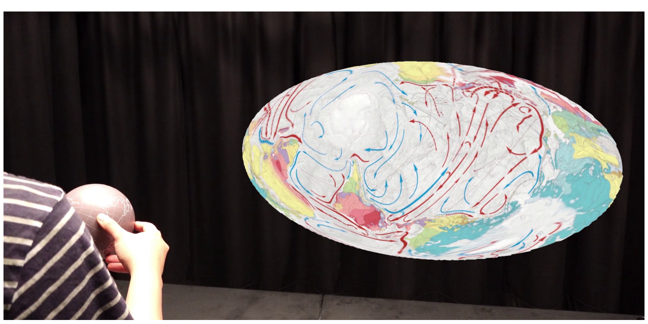

Figure 15: Tangible globe as a 3D controller for adjusting the centre and orientation of a flat world map (T3). Rotating the tangible globe applies the spherical rotation to an invisible virtual sphere, which is then projected to a flat map. The map shows global ocean currents (© Swiss Conference of Cantonal Ministers of Education (EDK), Swiss World Atlas [50]).

C1: Linked Charts. Geospatial data is usually multivariate and often visualised with idioms for abstract data such as bar charts or scatterplots. In this use case, we use the tangible globe to add geographical context to virtual charts. We visualise COVID-19 data using multiple virtual bar charts and a scatterplot and place them on the wall (Figure 16). When the user holds the tangible globe within a certain distance to the virtual charts, data points on the visible hemisphere of the tangible globe and the closest chart are connected with a 3D link [83], akin to the ImAxes proximity linking interaction [18, 19]. This is particularly useful to perform immersive brushing and linking operations to show geographical context of the points and bars on the scatterplot and bar charts.

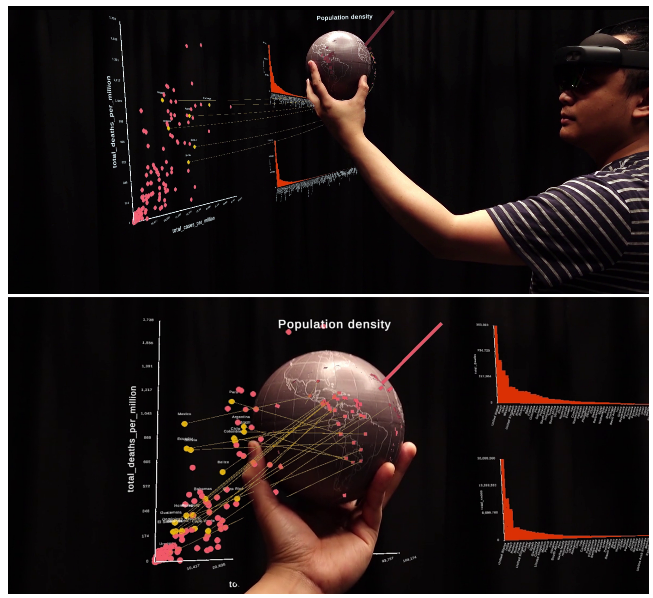

Figure 16: An example of complex interplay for visual analysis of COVID-19 data (C1). Virtual bars showing population density are aligned on the tangible globe surface. The scatterplot and bar charts are showing normalised total cases, normalised total deaths, total cases, and total deaths, respectively. Data: coronavirus pandemic (COVID-19) [85].

7 QUALITATIVE EVALUATION

After internal testing of the use cases, we conducted expert interview sessions to validate our ideas. The goals of the interviews were to gain feedback from external experts in cartography and immersive geovisualisation, to collect ideas for additional use cases, and to improve current use cases.

7.1 Procedure

We invited four experts from the fields of geographic data visualisation, cartography, and immersive analytics through our professional network (Table 1). Prior to the interview, we provided the participants with short video clips (the longest being 40 s) of all uses cases (A1–A4, T1–T3, and C1). These video clips can be seen in the video figure of this paper. Having access to the video clips allow

Table 1: Details about expertise of the 4 experts we interviewed.

Expertise domains	Organisation	Role
Immersive analytics , HCI, VR/AR	Federal University of Rio Grande do Sul, Brazil	PhD Candidate
Digital atlases, 3D cartography	ETH Zurich, Switzerland	Senior Researcher
Cartography, geographic storytelling	ESRI, Redlands, CA, USA	Story Maps Product Engineer
Visualisation, VR/AR, HCI, immersive analytics	Virginia Tech, VA, USA	Assistant Professor

experts to prepare their feedback in advance. During the interview session, we walked the participant through the three categories of virtual–tangible interplay and all use cases. For each use case, we asked the participants to play the video, then we asked them to concentrate their comments around the *what*, *who*, *why* and *how* data visualisation questions [76], but also allowed them to provide general feedback. Further questions were used to clarify participant's comments. The interviews were performed via video conferencing and lasted about 40 minutes per session.

7.2 Lessons Learned

We transcribed the interview recordings, extracted key points, and organised them using the affinity diagramming approach. This section summarises the feedback on all use cases. We outline significant lessons that we learned from the qualitative evaluation. The detailed summary of the feedback and comments for each use case is provided in Supplementary Material 3.

There is a need for incorporating geographic visualisation of smaller areas. Overall, the augmented globe use cases received positive comments as well as constructive criticisms. We learned from the expert feedback that registering data representations above (geographic flows A1) and on (texture overlay A4) the surface of a tangible globe works well for global patterns, however, when the focus is a smaller area, e.g. an individual country, a decoupled view of the focus area is probably better than a direct overlay (e.g. see Figures 17, 9–10). This indicates the need for supporting visual exploration at multiple level of scales [86–88].

Improvements on the composite chart. Arranging bars around the tangible globe (A2) was seen as an elegant way to show statistical data and geographical context but reading such visualisation requires learning. Labelling bars and interactive highlighting were suggested to improve readability.

The side-by-side constraint for visualising the hidden hemisphere may be too limiting. The criticisms around the side-by-side hidden hemisphere visualisation (A3) was mainly on the synchronised position between the virtual globe and tangible globe, which limits the use case to comparing countries that are 180° opposite each other. Decoupling the position and allowing the user to control the virtual globe tilt angle were proposed as possible improvements.

The exocentric large virtual globe received better acceptance than the egocentric globe. Despite being seen as an engaging use case by all experts, the inside-out egocentric globe was perceived as an unusual metaphor. However, experts commented that egocentric spherical visualisation may work for other applications, such as sky charts. Experts also thought that using a tangible globe for controlling an egocentric globe may conflict with other embodied interactions such as walking and gazing around. Experts also raised concerns about potential motion sickness with egocentric globes despite the transparent ocean in our use case.

Spherical rotation for adjusting the centre and orientation of a flat map (T3) could be a powerful educational tool, but may be a limited exploratory tool. Experts commented that spherical rotation was likely a useful educational tool to visualise the effect of globe rotation on map projections, but they also thought it may have a steep learning curve. Experts also suggested combining it with other use cases instead of using it as a standalone application.

Opportunities beyond statistical data. Our use cases are mainly showing statistical data but other types of data such as topographic or scientific data are worth exploring. As suggested by one expert, the composite chart could be used to visualise digital elevation data by overlaying the tangible globe with an exaggerated terrain visualisation and use the ring around it to show a terrain profile along a great circle.

Transitions between states in the design space. We confirmed from the interviews that, apart from adding more features and user interactions, making our use cases more useful for advanced data exploration requires combining multiple visualisations idioms and tools, and transitioning between visualisations with fluid animations.

8 DISCUSSION

8.1 Envisioning User Interactions

Our use cases developed so far focus mainly on the virtual presentation of information and contain limited exploration of the physical affordances of the tangible globe. This section highlights possible user interactions, including several ideas proposed during the interview sessions. Figure 17 illustrates the concepts explained below.

Rescale axis by pinch (Figure 17, 1). Axis rescaling is a common feature in interactive visualisation. Here, we focus on user interaction for the composite visualisation (A2) where the user can update the size of the visual data representation around the tangible globe. (Figure 17, 1) depicts the terrain profile visualisation suggested by one expert.

Select data layers by tap (Figure 17, 2). Layers are a crucial concept in geographic information systems. We envision that an improved AR visualisation with tangible globes would allow users to manipulate layers through a virtual panel situated next to the tangible globe, with tapping to toggle visibility or pinching to change the order of layers.

Details-on-demand by touch (Figure 17, 3). A virtual label showing detailed information would be useful for data exploration. For

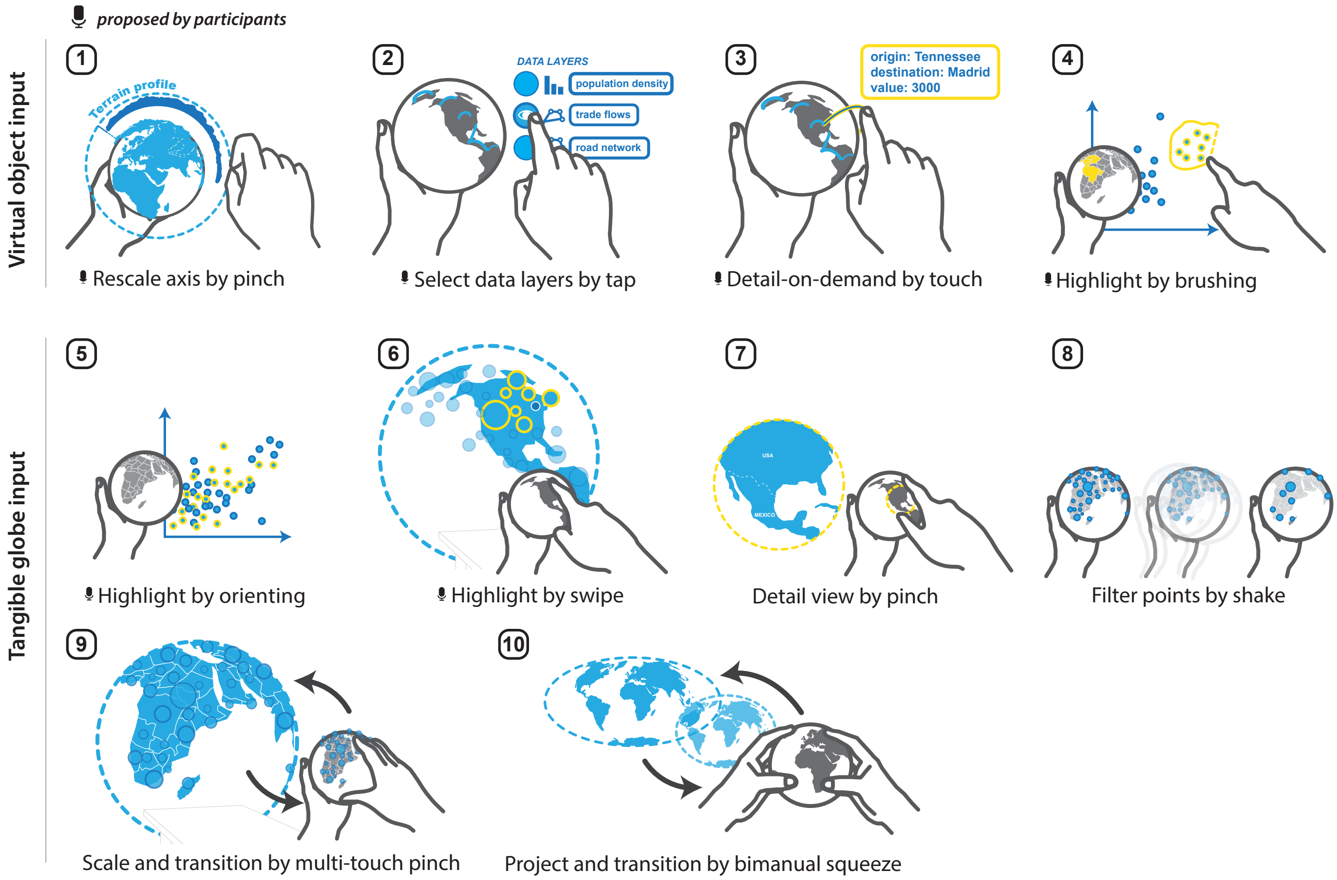

Figure 17: Some examples of hypothetical visualisations and user interactions based in part on interview responses. The first row shows user interactions facilitated by virtual object input while the second and last rows depict user interactions facilitated by the tangible globe input.

example, touching a flow line in A1 would reveal the origin, destination, and flow value.

Highlight by brushing (Figure 17, 4). One improvement that was suggested is a highlighting interaction where the user can brush a set of points on the statistical chart, which then highlights associated locations on the tangible globe.

Highlight by orienting (Figure 17, 5). The tangible globe could control highlighting of data points in linked charts, whereby data points that are shown on the currently visible globe hemisphere are highlighted.

Highlight by swipe (Figure 17, 6). The user could highlight visualisation marks on the virtual data representations, such as a large virtual globe (T1) using a swipe selection on the surface of the tangible globe.

Detail view by pinch (Figure 17, 7). This user interaction addresses the need for multi-scale exploration for geovisualisation, allowing the user to create a detail view by spreading two fingers on the tangible globe to specify the magnified area.

Filter points by shake (Figure 17, 8). Physical shaking of the tangible globe could be an embodied way to filter geographic data (as suggested by Newbury et al. [80] for virtual maps). For instance, repeated shaking could remove increasingly larger data points, perhaps cycling through the 25^{th}, 50^{th}, and 75^{th} data percentiles.

Scale and transition by multi-touch pinch (Figure 17, 9). This feature would allow the user to transition from an augmented globe (A1 – A4) to an exocentric virtual globe (T1) by spreading their fingers and thumb on the tangible globe, then spreading or pinching their fingers to control the scale of the virtual globe.

Project and transition by bimanual squeeze (Figure 17, 10). This user interaction allows the user to transition between an augmented globe and a 2D map projection by squeezing the tangible globe with both hands.

8.2 Beyond Small Tangible Globes

We presented our use-cases with a small hand-held globe, but most of these concepts are transferable to medium size globes (Figure 18, top-left). Although *free* medium-sized globes are not as comfortable to hold [31] and bimanual grasps limit interaction, *constrained* medium globes placed on a table can be more easily combined with tangible input (Figure 18, top-right).

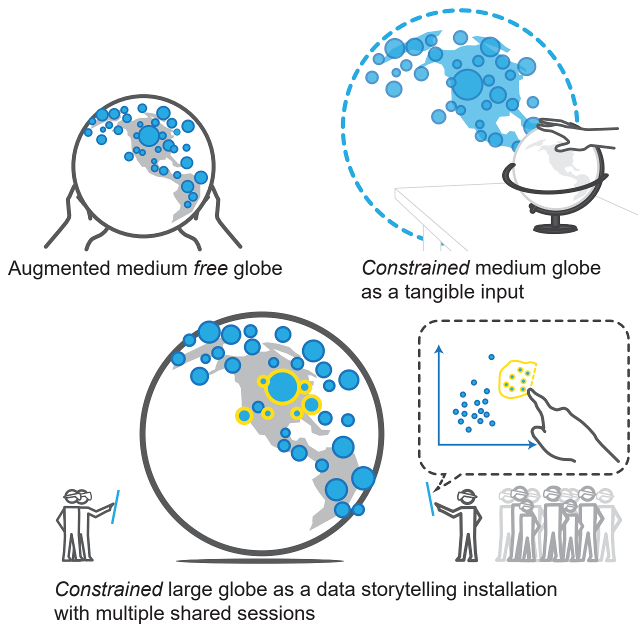

Figure 18: Our envisioned scenarios of medium and large tangible globes for data visualisation in augmented reality. The bottom figure shows group collaboration (left) and presentation (right) scenarios with large augmented tangible globe. On the bottom right is a presenter performing the "shared highlight by brushing" interaction.

For large globes, direct tangible interaction is limited. However, augmented reality data visualisation with large tangible globes will provide a useful medium for geographic story telling. Figure 18, bottom, illustrates two groups of users, with each group creating their own visualisation. The two users on the left share one view while the tour leader on the right shares another view with a larger audience. The tour leader groups data points on an AR scatterplot to tell a story to the audience. In-air AR panels are used to create visualisation on and around the globe by both groups.

8.3 Significance of Work

This work introduces a set of design dimensions for combining tangible globes with virtual data representations, and reveals an uncharted space for tangible-virtual interplay of data visualisation on globes. In this initial exploration, we focused on exploring use cases with a small, hand-held tangible globe for augmented reality data visualisation. While existing related work used medium size spheres as input devices and demonstrated more variety of *interaction modes*, these are independent works with different aims, including navigation in VR with spherical input [28, 30], 3D objects manipulation in AR [27], and enhancing perception of spherical data representation in VR [25, 31].

Our work is, to our knowledge, the first attempt to explore the design space and congregate a wide range of use cases of data visualisation in augmented reality with tangible globes. This is reflected in Figure 4, where our work presents a wider variety of visualisation idioms (A1, A2, A3, T1, T3, C1); reference frames such as around the tangible globe (A2), side-by-side with the globe (A3), and anchored in the physical environment (T1, T2, T3, C1); orientations such as billboard orientation (A2), free rotation (T1, T2, T3); as well as multiplicity (T2, C1). We also introduce a concept to manipulate the map projection centre point using a tangible globe (T3). While our use cases lack user interaction beyond tangible manipulation, we provide a set of ideas for interaction to enrich the data exploration experience. By focusing on data visualisation design, our work can be a source of inspiration for immersive data visualisation designers, in particular those who are interested in incorporating tangible globes. Our use case implementations show the wide variation of designs available within each of the three categories of tangible-virtual interplay we defined. This variation demonstrates the *generative* potential of our design space [2]. Our application of this design space to describe existing designs from related work in Figure 4 also shows its *descriptive* and *comparative* potential.

9 LIMITATIONS, FUTURE WORK, AND CONCLUSION

We acknowledge several limitations of our exploration of augmented reality data visualisation with tangible globes. Our qualitative evaluation with experts revealed initial impressions, potential improvements, and ideas for further exploration. However, the low number of participants and their experience via video only, rather than direct first-hand experience of the use cases, limit the generalisability of our findings. Moreover, the presented virtual-interplay categories and use cases are potentially limited by the relatively small size of the tangible globes prototypes we created. Future comparison studies will likely reveal benefits of different tangible globe sizes, interaction modalities, or trade-offs of different virtual visualisation idioms for tangible globes.

Our experience with the implemented use cases suggests that while virtual object registration can be made accurate when the tangible globe is in a stationary position, slight drifting and flickering become apparent while the tangible globe is translated. We see registration errors of up to 5 mm and latency between 75 ms and 100 ms. We suspect that these errors are caused by inaccuracies of the QR marker registration and the Vicon object's centre point positioning. As discussed in earlier sections, inaccurate registration can be an issue for visualisation idioms that require precise placement of visual geometries, such as bars and flows lines in A1 use case. While our implementation relies on an external tracking system, we envision future AR devices will provide more robust object recognition and tracking.

This work explores the design space of tangible globes for data visualisation with AR, and reveals the wide variety of available geospatial data visualisations in this space. Our design space infers dimensions from prior work on tangible globes on the one hand and virtual data representation on the other hand. From this design space we distil three main categories of use cases which we exemplify with the implementation of a set of example use cases using a tangible globe prototype. These examples demonstrate specific opportunities for using tangible globes in AR to support analysis of existing data sets. Our work shows how the centuries old globe can be combined with emerging AR technology to inspire completely new ways of viewing and interacting with geospatial data. We hope our contributions assist the development of immersive analytics systems that better support human sense-making and decision making.

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